

# Much improved self-organized $\text{In}_{0.53}\text{Ga}_{0.47}\text{As}$ quantum wire lasers grown on (775)B InP substrates by molecular beam epitaxy

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**Abstract.** A self-organized  $\text{In}_{0.53}\text{Ga}_{0.47}\text{As}/(\text{In}_{0.53}\text{Ga}_{0.47}\text{As})_2(\text{In}_{0.44}\text{Al}_{0.56}\text{As})_2$  quantum wire (QWR) laser was grown on a (775)B InP substrate by molecular beam epitaxy (MBE). Well lattice-matched and flat cladding layers were grown at a rather high temperature (595° C). Lateral confinement potential was induced by a nano-meter scale interface corrugation of  $\text{InGaAs}/(\text{InGaAs})_2(\text{InAlAs})_2$  with an amplitude of 2 nm and a period of 40 nm. A 50  $\mu\text{m}$  x 500  $\mu\text{m}$  stripe-contact QWR laser with uncoated cleaved mirrors oscillated with a threshold current density ( $J_{\text{th}}$ ) of 1.2 kA/cm<sup>2</sup> and a lasing wavelength of 1370 nm at 250 K under pulsed current condition.

## 1. Introduction

Recently, semiconductor low-dimensional structures such as quantum wires (QWRs) and quantum dots (QDs) have been intensively studied due to their high application potential for new optoelectronic devices. Reduction of dimensionality leads to sharp peaks in the density of states, resulting in new phenomena and further improvements of device performance.<sup>1-3)</sup> Numerous studies have been reported on the fabrication methods of semiconductor QWRs such as etching and regrowth method using electron beam (EB) lithography,<sup>4)</sup> cleaved edge overgrowth (T-QWRs),<sup>5-7)</sup> and growth on non-planar substrates (ridge<sup>8,9)</sup> or V-groove<sup>10-12)</sup> QWRs). Self-organization technique of the QWR structure is one of the most attractive methods for optical devices, because of high QWR density, high uniformity, high optical quality and easy fabrication. Especially, self-organized QWRs using corrugated heterointerfaces grown on (775)B-oriented have great potential for QWR lasers, because of their higher density and rather good uniformity comparing to the other self-organized QWRs.<sup>13-17)</sup> Strictly speaking, this (775)B plane should be expressed as a (577)B plane which is 8.5° off from (111)B

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toward (011). In this paper, however, we use a word of “(775)B plane” instead of “(577)B plane” just for convenience.

We reported a self-organized (775)B GaAs/(GaAs)<sub>4</sub>(AlAs)<sub>2</sub> QWR laser and In<sub>0.1</sub>Ga<sub>0.9</sub>As/(GaAs)<sub>4</sub>(AlAs)<sub>2</sub> QWR laser with a stripe-contact graded index separate confinement heterostructure (GRIN-SCH), which oscillated with emission wavelengths of 760 nm and 868 nm, respectively, at 20°C.<sup>14-16)</sup> We also reported laser oscillation of self-organized (775)B InGaAs/(InGaAs)<sub>2</sub>(InAlAs)<sub>2</sub> QWR lasers on InP substrates<sup>17)</sup> with an emission wavelength of 1215 nm and a rather high threshold current density ( $J_{th}$ ) of 5.2 kA/cm<sup>2</sup> at 150K. In this paper, we report that self-organized (775)B InGaAs/ (InGaAs)<sub>2</sub>(InAlAs)<sub>2</sub> QWR lasers with an improved cladding layer grown on (775)B-oriented InP show much improved threshold current density and operation temperature.

## 2. MBE GROWTH OF CLADDING LAYERS

Growth-temperature ( $T_s$ ) dependence of the 1μm-thick InGaAs(1nm)/InAlAs(9nm) superlattice (SL) cladding layer was investigated to obtain flat surface of the cladding layer. (775)B-oriented InP substrates were heated up to 570°C for a few minutes in As<sub>4</sub> atmosphere ( $\sim 10^{-6}$  Torr) just prior to molecular beam epitaxy (MBE) growth to remove native oxides on an InP surface. Figure 1 shows the atomic force microscopy (AFM) surface image of a 1μm-thick InGaAs(1nm)/InAlAs(9nm) superlattice cladding layer grown at  $T_s$ =505, 535, 570 and 590°C. Each cladding layer is lattice-matched within indium content  $x = 0.52 \pm 0.01$ . The top layer was 1nm-thick InGaAs. Indium desorption is so large at the higher growth temperature (580°C~595°C), we must increase indium growth rate by 1% to 4% of indium flux. As shown in Fig. 1, the surface of InGaAs/InAlAs superlattice cladding layer grown at less than 570 °C has large corrugation with a period of  $\sim 160$  nm. The amplitude of the corrugation decreases drastically with increasing the growth temperature. Actually, the amplitude of the corrugation is 10 nm ( $T_s = 505$  °C), 9 nm (535 °C), 5 nm (570 °C), and 1 nm (590 °C). We adopt  $T_s = 595$  C for the growth of the cladding layer to prevent formation of the corrugation due to slight decrease of substrate temperature during growth.

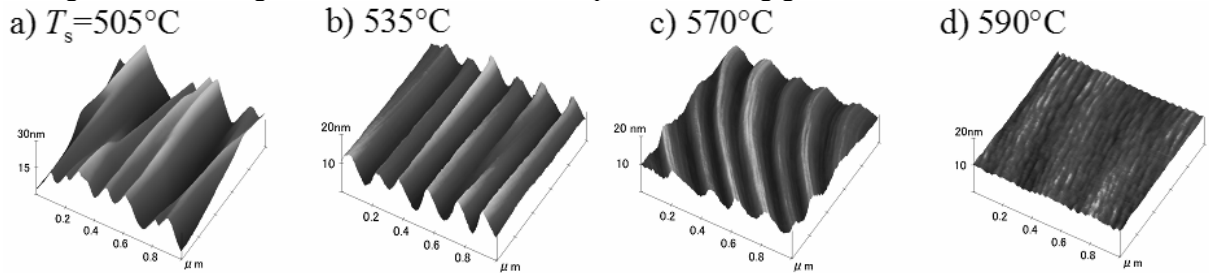


Figure 1 AFM images of the top InGaAs layer of 1 m-thick InGaAs (1nm)/ InAlAs (9nm) cladding layer grown at 505°C (a), 535°C (b), 570°C (c), 590°C (d) on (775)B InP substrates by MBE.

## 3. LASER STRUCTURE

Figure 2 shows a schematic structure of a self-organized In<sub>0.53</sub>Ga<sub>0.47</sub>As/(In<sub>0.53</sub>Ga<sub>0.47</sub>As)<sub>2</sub>(In<sub>0.44</sub>Al<sub>0.56</sub>As)<sub>2</sub> QWR laser grown on (775)B InP substrates by MBE. After preparing flat In<sub>0.53</sub>Ga<sub>0.47</sub>As(1 nm)/ In<sub>0.52</sub>Al<sub>0.48</sub>As (9 nm) SL cladding layers at  $T_s = 595$  ° C, five In<sub>0.53</sub>Ga<sub>0.47</sub>As (3.6 nm)/(In<sub>0.53</sub>Ga<sub>0.47</sub>As)<sub>2</sub>(In<sub>0.44</sub>Al<sub>0.56</sub>As)<sub>2</sub> (10.2 nm) QWR layers and (In<sub>0.53</sub>Ga<sub>0.47</sub>As)<sub>2</sub>/(In<sub>0.52</sub>Al<sub>0.48</sub>As)<sub>4</sub> SCH barrier layers (150 nm thick) were grown at lower growth temperature ( $T_s = 580$ °C) to obtain the surface corrugation. V/III pressure ratio was 10. Si- and Be-doping concentrations of the buffer layers and the clad layers were about  $2 \times 10^{18}$  cm<sup>-3</sup>.

Figure 3 shows AFM surface images of InGaAs QWR layer (surface A in Fig.3) and (InGaAs)<sub>2</sub>(InAlAs)<sub>2</sub> barrier layer (surface B in Fig.3). Those surfaces were prepared by growing the same structure up to the interface indicated by A and B in Fig.2 and the top layer of the

(InGaAs)<sub>2</sub>(InAlAs)<sub>2</sub> SL barrier layer surface is (InAlAs)<sub>2</sub>. Corrugated surfaces with rather straight step edges along [110] can be seen for both of InGaAs and InAlAs surfaces. The (InGaAs)<sub>2</sub>(InAlAs)<sub>2</sub> barrier surface has more regular corrugation with almost the same amplitude (2 nm) and the lateral period (40 nm), while the InGaAs QWR surface has the smaller amplitude of corrugation. Hence, it is expected that the thickness modulation of the InGaAs QWR layer induce the lateral confinement potential for electrons and holes.

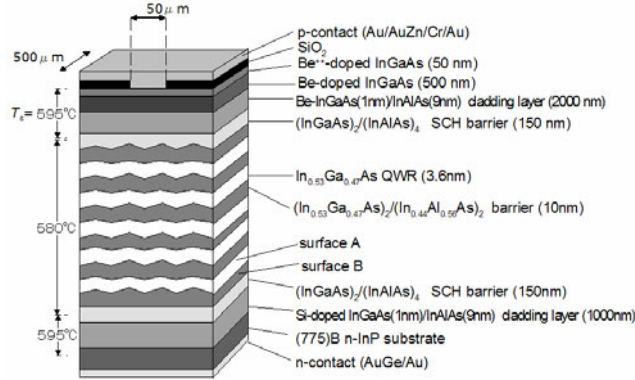


Figure 2. A Schematic illustration of a stripe-contact SCH In<sub>0.53</sub>Ga<sub>0.47</sub>As/ (In<sub>0.53</sub>Ga<sub>0.47</sub>As)<sub>2</sub>(In<sub>0.44</sub>Al<sub>0.56</sub>As)<sub>2</sub> QWR laser structure grown on a (775)B InP substrate by MBE.

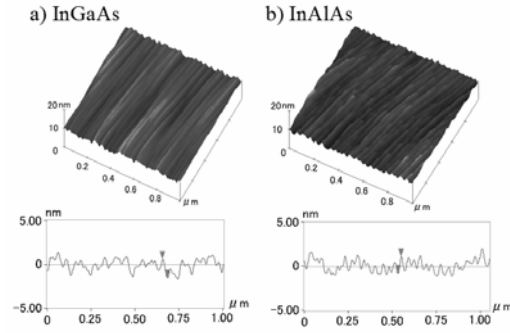


Fig. 3. AFM images of the InGaAs QWR layer on (In<sub>0.53</sub>Ga<sub>0.47</sub>As)<sub>2</sub>(In<sub>0.44</sub>Al<sub>0.56</sub>As)<sub>2</sub> short period superlattice (SPS) barrier layer (a) and the InAlAs surface of (In<sub>0.53</sub>Ga<sub>0.47</sub>As)<sub>2</sub>(In<sub>0.44</sub>Al<sub>0.56</sub>As)<sub>2</sub> SPS barrier layer (b), on (775)B InP substrates by MBE

#### 4. POLARIZATION PL FROM QWR LASER

Polarization dependent PL measurements on the QWR active layer of the laser structure (Fig. 2) were carried out, before depositing metal contact layers, at RT with a Ti-sapphire laser ( $\lambda = 830$  nm) for excitation. The InGaAs cap layer was stripped by wet-chemical etching using adipic-acid-based solution<sup>18)</sup>. The laser beam was focused on a sample surface area of a diameter of about 200  $\mu$ m, and PL spectra were observed by a monochromator and a photomultiplier with an InGaAs photocathode. Figure 4 shows polarized PL spectra from the (775)B InGaAs QWR active layer.

Solid lines and dashed lines illustrate PL spectra for polarization parallel and perpendicular to the QWRs, respectively. The PL intensity from present sample was about 100 times stronger than that of previous laser structure. The full width at half maximum (FWHM) of the PL peak was 47 meV at RT, and the emission wavelength was 1381 nm at RT (69 meV and 1300 nm for previous laser respectively). Although nominal structures of the laser active region in this work and in previous work were almost same, the previous laser shows an 81 nm shorter PL emission wavelength. This is because greater part of the previous laser was grown at 540 °C where the lattice-match condition was fulfilled and its active region was grown at 605 °C under the same fluxes of all sources, which caused reduction of the indium content. Polarization degree  $P [\equiv (I_{\parallel} - I_{\perp}) / (I_{\parallel} + I_{\perp})]$  of the PL peaks from the (775)B QWRs was as high as 0.10, indicating that high quality QWRs were fabricated on (775)B InP substrates.

#### 5. I-L CHARACTERISTICS OF LASER DIODES

SCH QWR lasers with a stripe width of 50  $\mu$ m and a cavity length of 500  $\mu$ m were fabricated (Fig. 2). The electric current versus light output ( $I$  -  $L$ ) curves were measured under the condition of pulsed current (Fig.5). The pulse width and repeat period were 6  $\mu$ s and 2 ms, respectively. Emission from the lasers was detected by an optical power sensor (ANRITSU). Fabry-Pérot mirrors of the (775)B InGaAs/(InGaAs)<sub>2</sub>(InAlAs)<sub>2</sub> QWR lasers were formed with uncoated cleaved (110) planes. The cavity direction was parallel to the QWR. The (775)B QWRs perpendicular to the laser cavity are

considered to provide a better optical gain, but cleaved planes cannot work as the Fabry-Pérot mirror for the (775)B QWR lasers with the cavity perpendicular to the QWRs. Figure 5 shows I-L characteristics of the (775)B QWR laser observed at 210 K, 250 K and 260 K. The inset of Fig. 5 is lasing spectra at 250 K (260 mA). This (775)B QWR laser oscillated with a lasing wavelength of 1370 nm at 250 K. Threshold current densities were  $0.76 \text{ kA/cm}^2$  (210 K),  $1.0 \text{ kA/cm}^2$  (250 K) and  $1.2 \text{ kA/cm}^2$  (260 K), respectively. We need further improvement of optical quality of QWRs to reduce the jth and to achieve laser oscillation at RT.

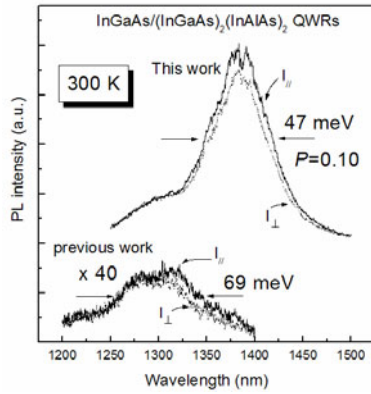


Figure 4. Polarized PL spectra from the (775)B InGaAs QWRs. Solid lines ( $I_{\parallel}$ ) (dashed lines ( $I_{\perp}$ )) indicates PL spectra for polarization parallel (perpendicular) to the QWR for the (775)B sample.

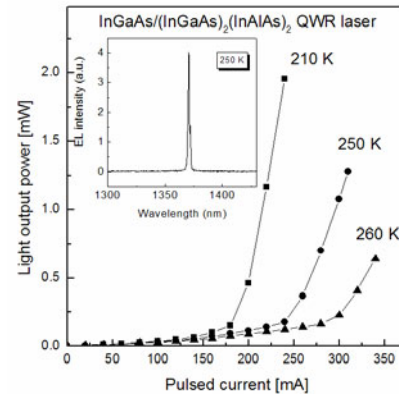


Figure 5. Electric current versus light output (I-L) for the (775)B InGaAs QWRs lasers. The inset is the lasing spectrum at just above threshold current (260 mA).

## 6. CONCLUSION

A self-organized  $\text{In}_{0.53}\text{Ga}_{0.47}\text{As}/(\text{In}_{0.53}\text{Ga}_{0.47}\text{As})_2(\text{In}_{0.44}\text{Al}_{0.56}\text{As})_2$  QWR laser structure was grown on a (775)B InP substrate by MBE. Stripe contact type SCH QWR lasers with a stripe width of  $50 \mu\text{m}$  and a cavity length of  $500 \mu\text{m}$  were fabricated. The (775)B QWR laser oscillated at  $J_{\text{th}} = 1.2 \text{ kA/cm}^2$  at 260 K under the condition of pulsed current. The oscillation wavelength was 1370 nm at 250 K. The operation temperature and  $J_{\text{th}}$  were dramatically improved compared to our previous laser ( $J_{\text{th}} = 5.2 \text{ kA/cm}^2$  at 150 K). The result indicates that high quality QWRs were fabricated on (775)B InP substrates.

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